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CFD methods for wind turbine aerodynamics

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CFD Methods For Wind Turbine Aerodynamics

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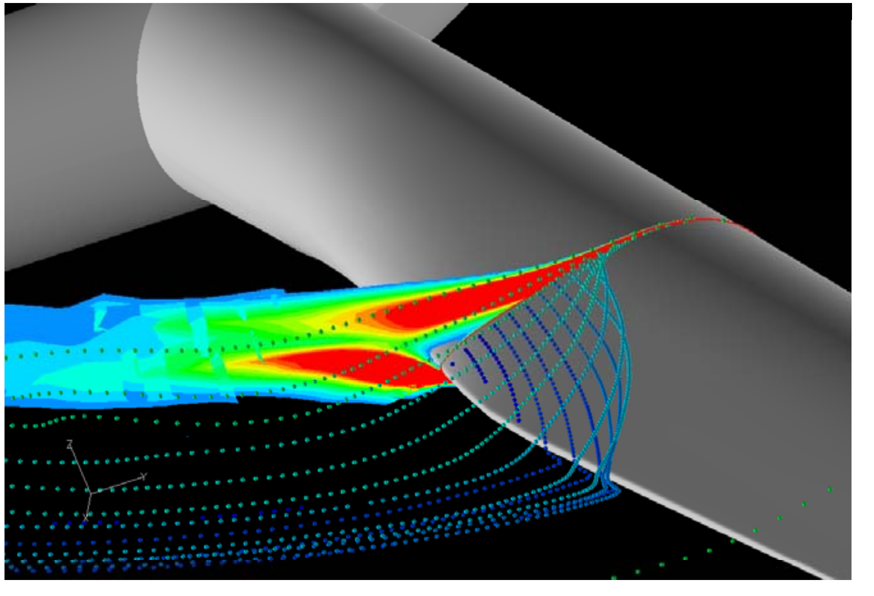
National Laboratory for Sustainable Energy



Risø's history in brief

- **1956** Peaceful utilisation of nuclear energy
- **1976** Nuclear energy and other energy sources
- **1986** Energy research in general
- **1990** R&D with energy as the primary area
- **1994** State-owned enterprise
- **2000** The last nuclear reactor is decommissioned
- **2005** Impact within
  1. Technology for greater competitiveness
  2. Sustainable energy supply
  3. Health technology
- **2007** Merger with DTU, National Laboratory for Sustainable Energy

Outline of talk

- Aerodynamics of wind tubines
- CFD in Wind Turbine Aerodynamics
  - General Overview
  - The EllipSys2D/3D solvers
- Applications
  - Airfoil Aerodynamics
  - Transition modeling
  - Dynamic stall
  - Deep stall aerodynamics
  - Rotor aerodynamics
  - Aeroelasticity
  - Flow over terrain

Aerodynamics for wind turbines

- Flow over complex terrain
- Rotor aerodynamics
- Rotor/Tower interaction
- Wake aerodynamics
- Airfoil Flows
- Laminar/turbulent transition
- Hysteresis phenomena, dynamic stall
- Damping and stability
- Aeroelasticity

Development and origin of CFD for Wind Energy

- The application of numerical methods to fixed wing and rotor aerodynamics dates back to the late seventies in the aerospace community, solving steady Potential and Euler equations.
- The first unsteady solution to the Euler equations were seen through the eighties.
- With the continuous increase in computer power in the late eighties and early nineties the first Reynolds Averaged Navier-Stokes codes for helicopter applications appeared.
- With the possibility of handling viscous flow, the first applications of Navier-Stokes CFD solvers appeared in the wind turbine community in the late nineties.
- In Europe a series of EU-financed projects were providing the basis for many of these activities.

Components of a CFD method

The basic idea is to take the partial differential equations describing the fluid flow, transform them into a set of algebraic equations, and solve these using a numerical method on a computer.

Typical components of a CFD code are listed below:

- Mathematical Model
  - Compressible/Incompressible
  - Potential/Euler/Navier-Stokes
  - Turbulence Modeling
- Coordinate and basis vector systems
- Discretisation method, space and time
  - Finite Difference/ Finite Volume/ Finite Elements
- Solution Method
- Computational Grid

Turbulence Modeling

- Direct Numerical Simulation (DNS)

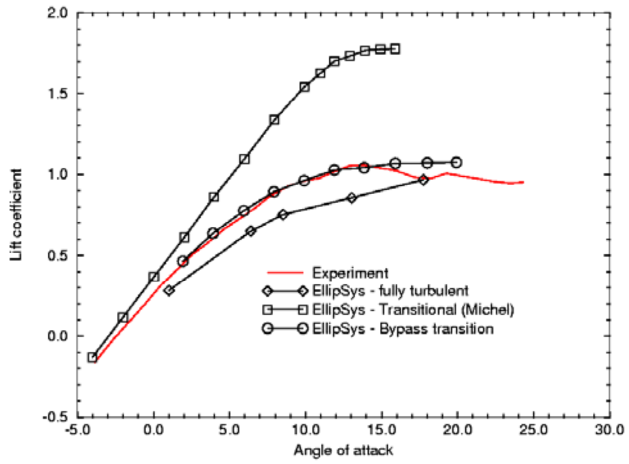
- Filtered Equations
  - Large Eddy Simulation (LES)

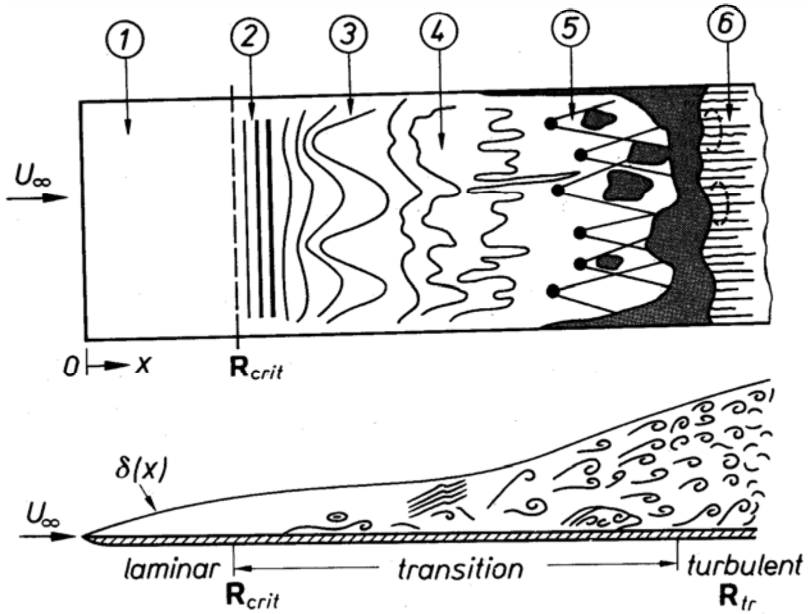
- Time Averaged Equations, Reynolds Averaged Navier-Stokes(RANS)
  - Algebraic Models (e.g. Baldwin-Lomax)
  - One Equations Models (e.g. Spalart-Allmaras, Baldwin-Barth)
  - Two Equation Models (e.g. k-ω, k-ε)
  - Reynolds Stress Models

- Hybrid Models
  - Detached Eddy Simulation

Laminar to Turbulent Transition

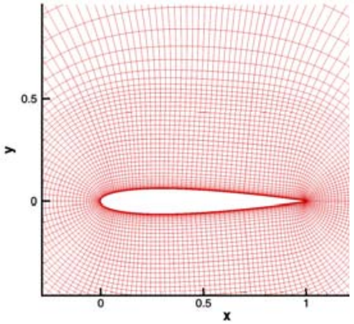
- Michel Model
- e^n-model (Data base)
- Bypass transition
- Correlation based transition

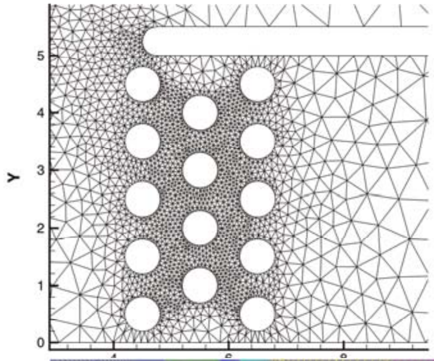


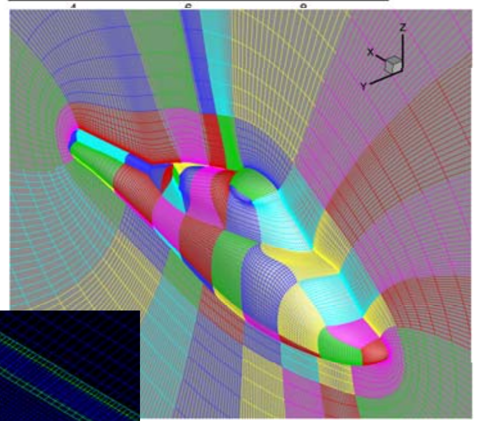


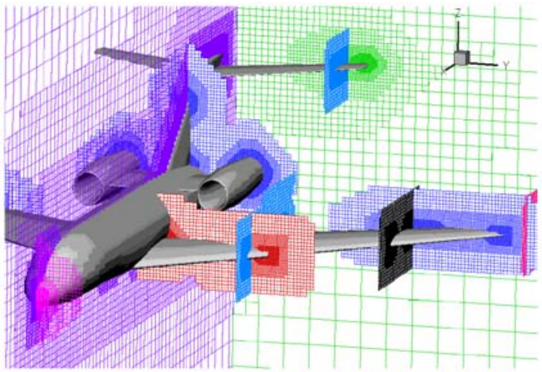
Computational Grid

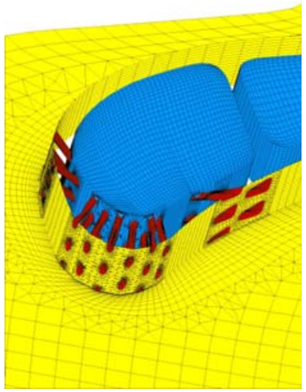
- Structured
- Unstructured
- Multi-block
  - Different type of conforming grids
  - Overlapping or Chimera
- Hybrid Meshes (Structured/ Unstructured)
- Cartesian Cut Cells

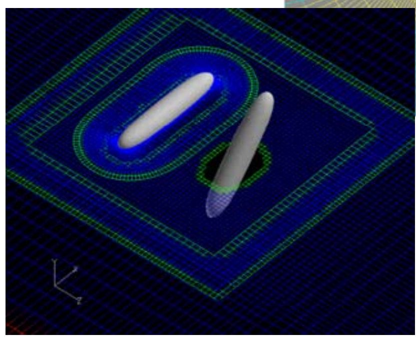




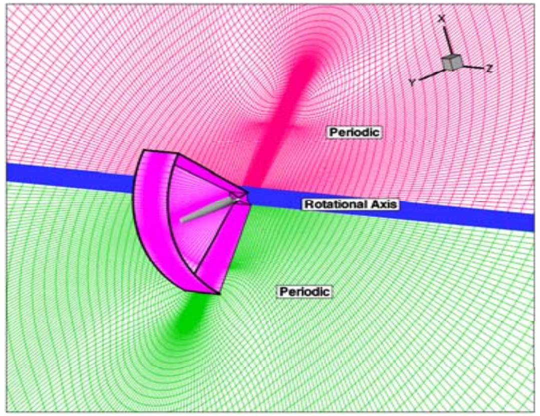


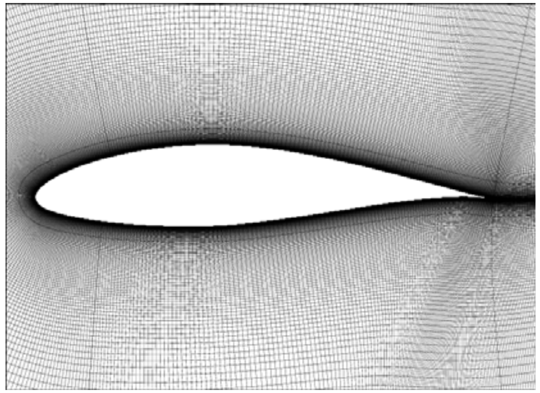






Ellipsys2D / 3D
The choices in our flow solver





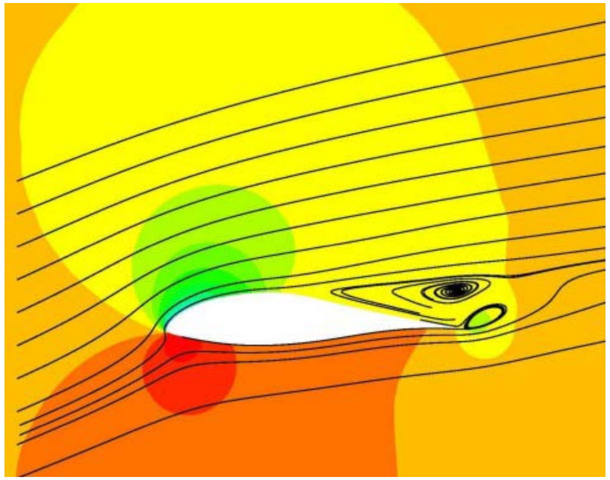
- Incompressible Navier-Stokes
- Finite volume code (non-staggered)
- Cartesian or polar velocity components
- Patched multi-block grids (new overset option)
- Pressure/Velocity formulation
- Steady/Unsteady algorithm
- Moving Mesh/Moving Frame
- Turbulence Modelling RANS/DES
- Acceleration techniques: grid sequence/multi-grid
- Parallellized using MPI for distributed computers

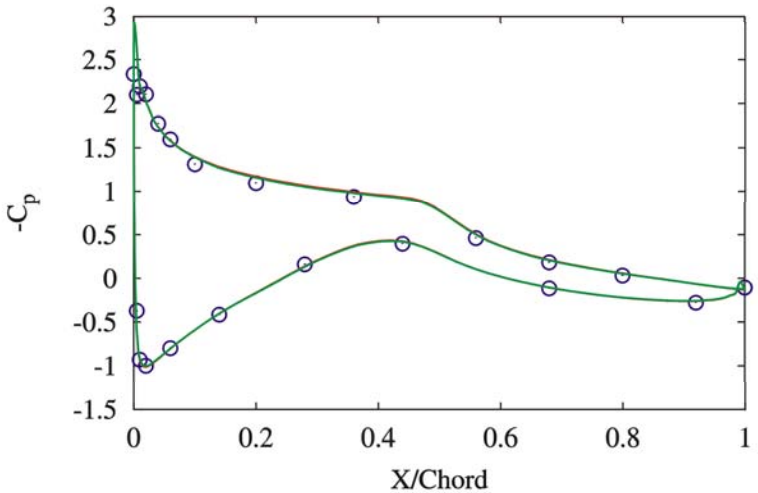
$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho U_j) = 0 \ ,$$

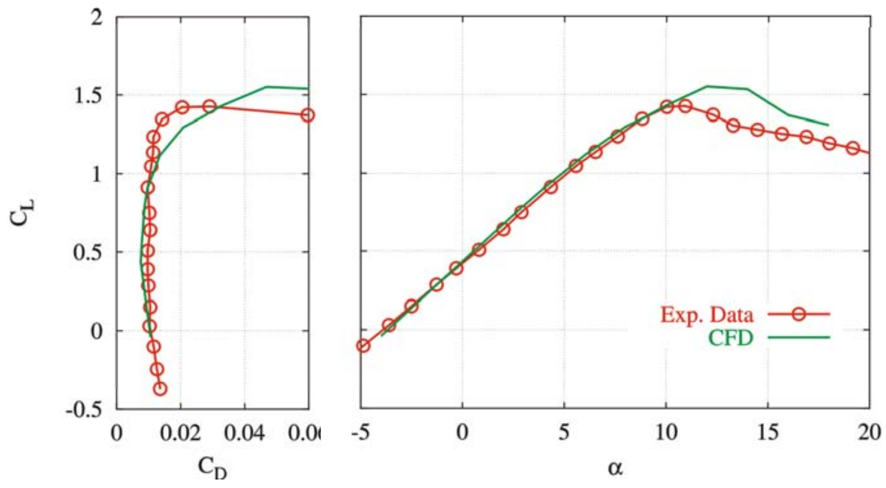
$$\frac{\partial}{\partial t}(\rho U_i) + \frac{\partial}{\partial x_j}[\rho U_i U_j] - \frac{\partial}{\partial x_j}\left[(\mu + \mu_t)\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\right] + \frac{\partial P}{\partial x_i} = S_{\boldsymbol{v}} \ ,$$

Airfoil Aerodynamics
2D applications

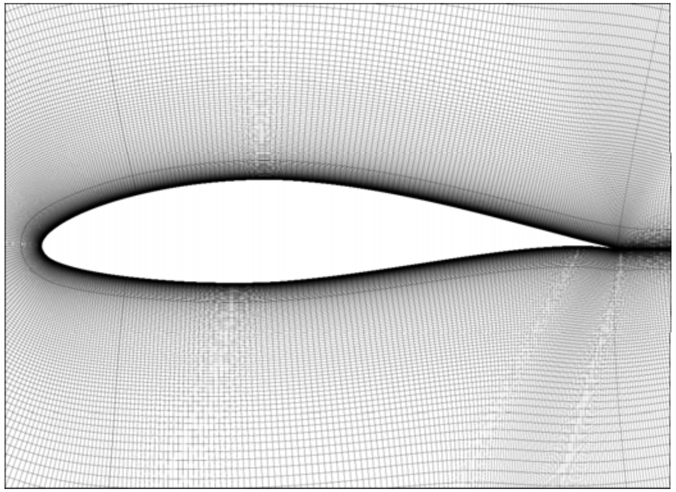
- Basic studies
- Cl/Cd/Cm for BEM computations
- Airfoil catalog
- Airfoil design and optimization
- Planning and conduction of measurements
- Laminar/turbulent transition
- Dynamic stall computations





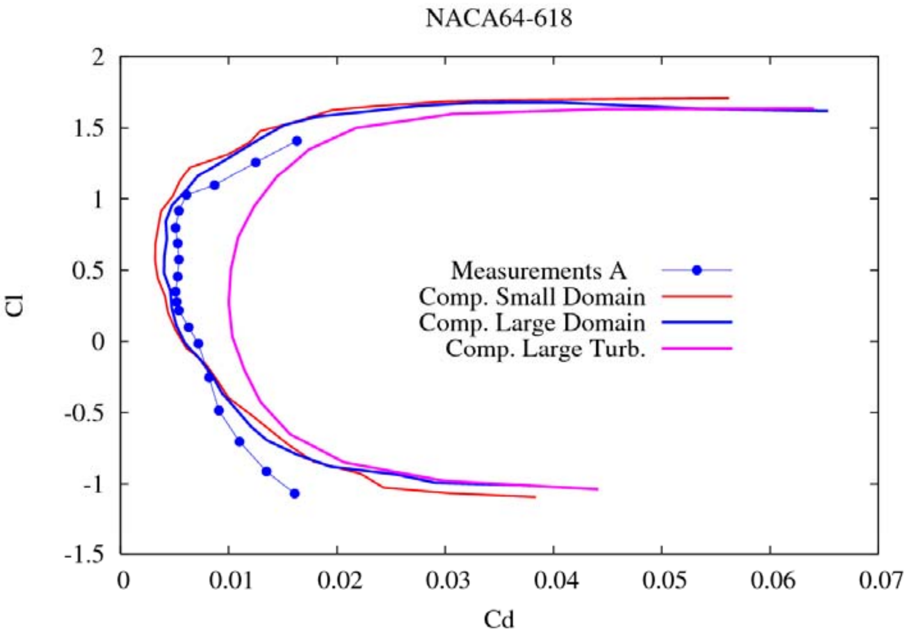


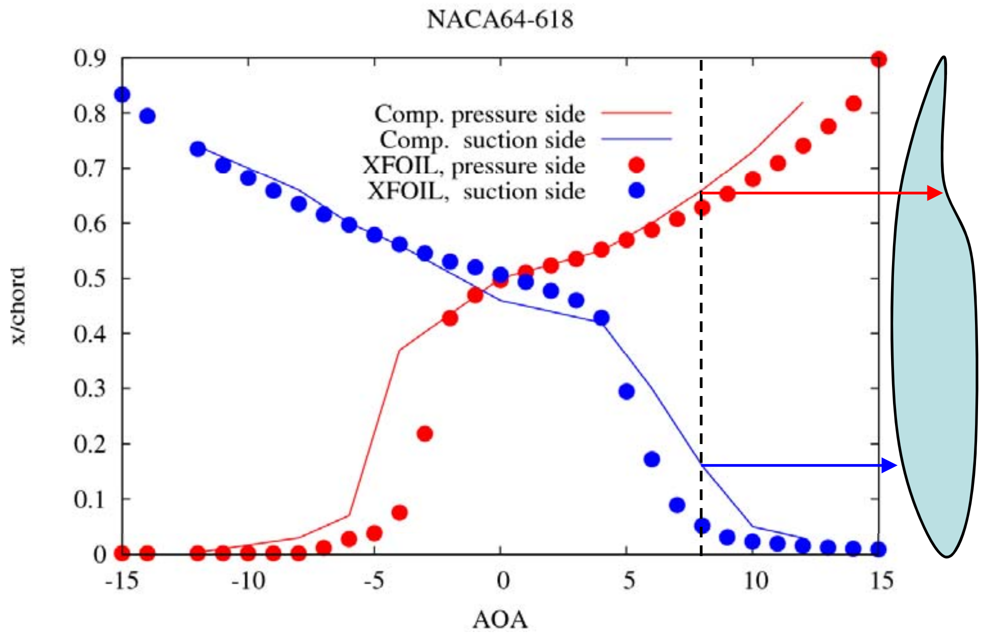
Airfoil Aerodynamics
Laminar / Turbulent transition



NACA 64-618, Re=6.0 million

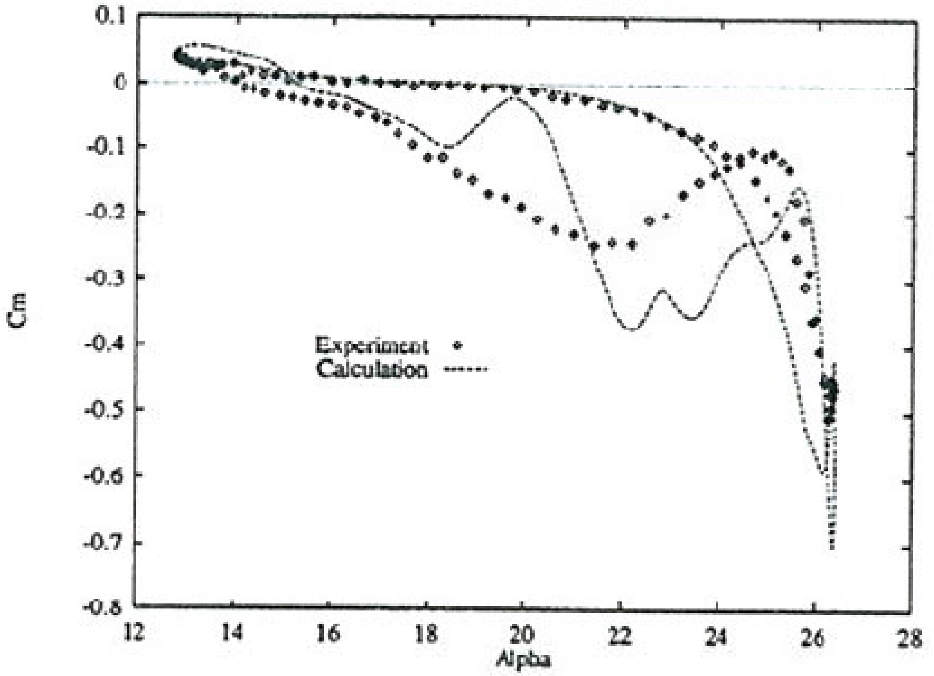
- C-mesh with 512x128 cells
- Wall normal distance: $y^+<1$
- Maximum expansion rate: < 5%
- Inflow turbulence intensity 0.009%

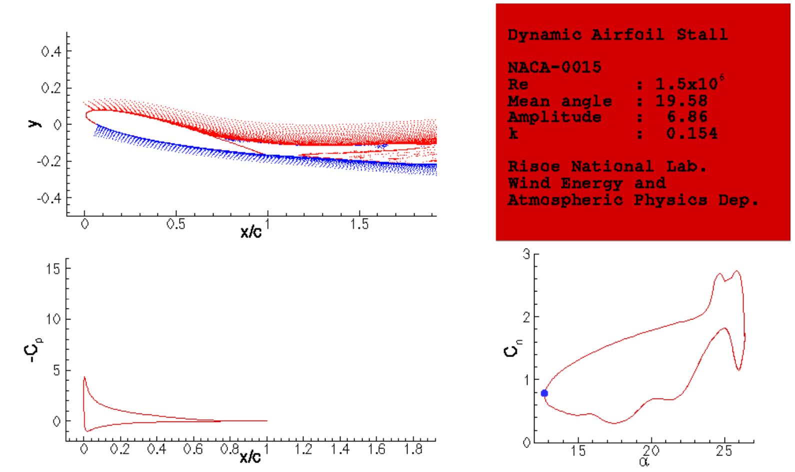




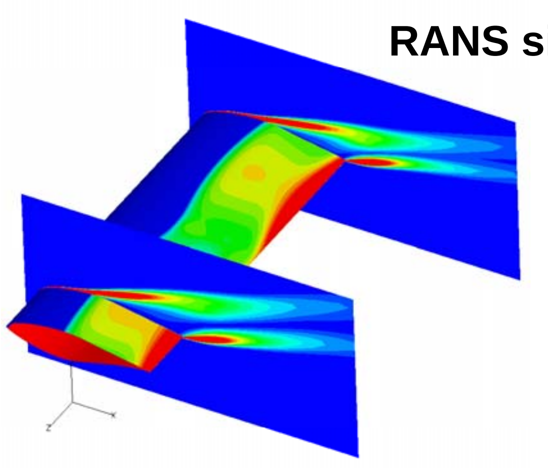
Airfoil Aerodynamics
Dynamic stall

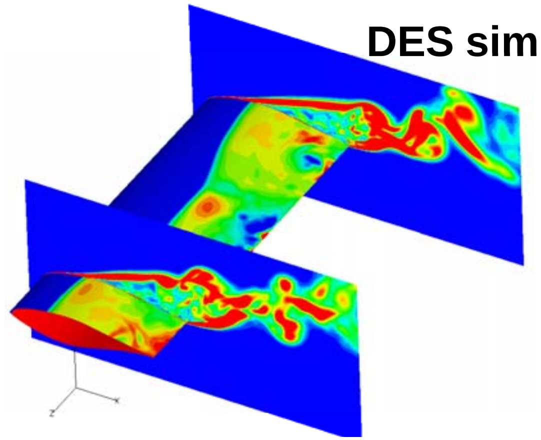
- Dynamic stall
- Stall characteristics
- Aerodynamic damping



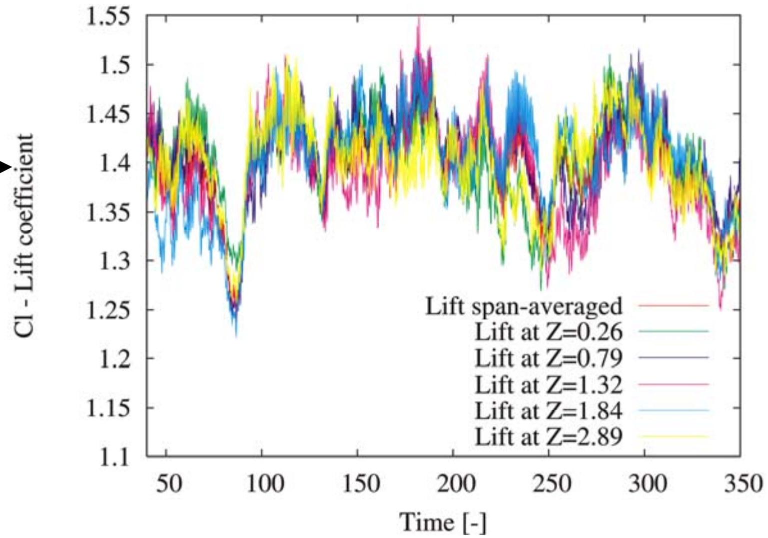


Deep Stall Aerodynamics
3D blade section in static stall





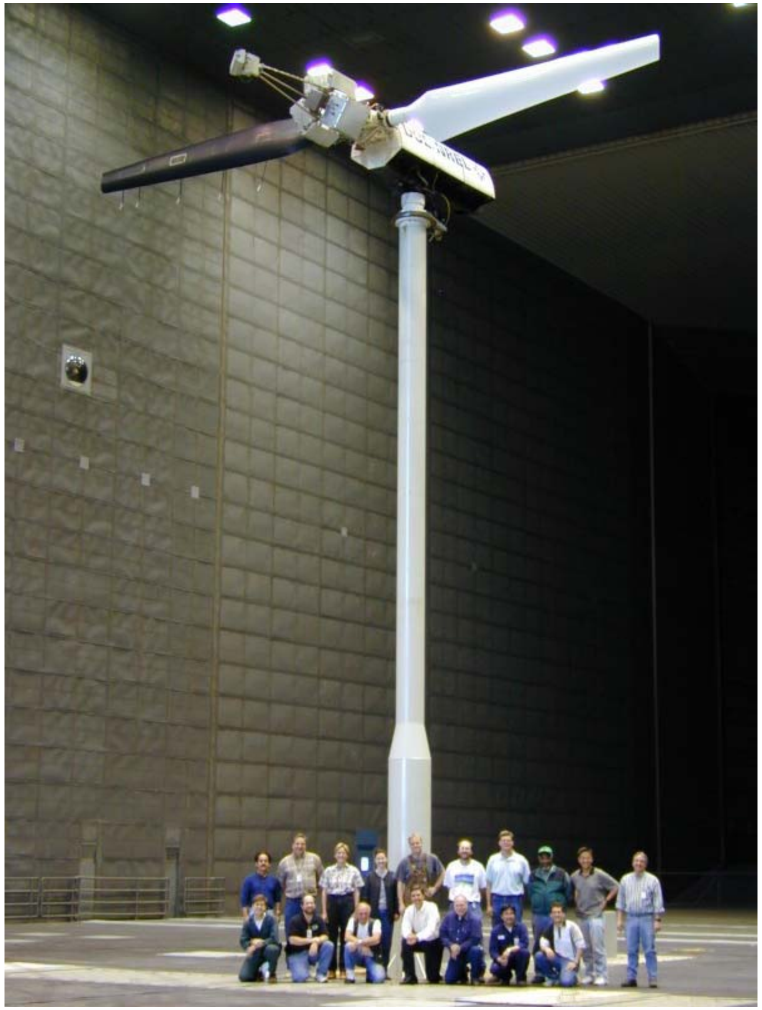
Unsteady lift time series



The development of a stochastic stall-model based on time series from DES-simulations is ongoing

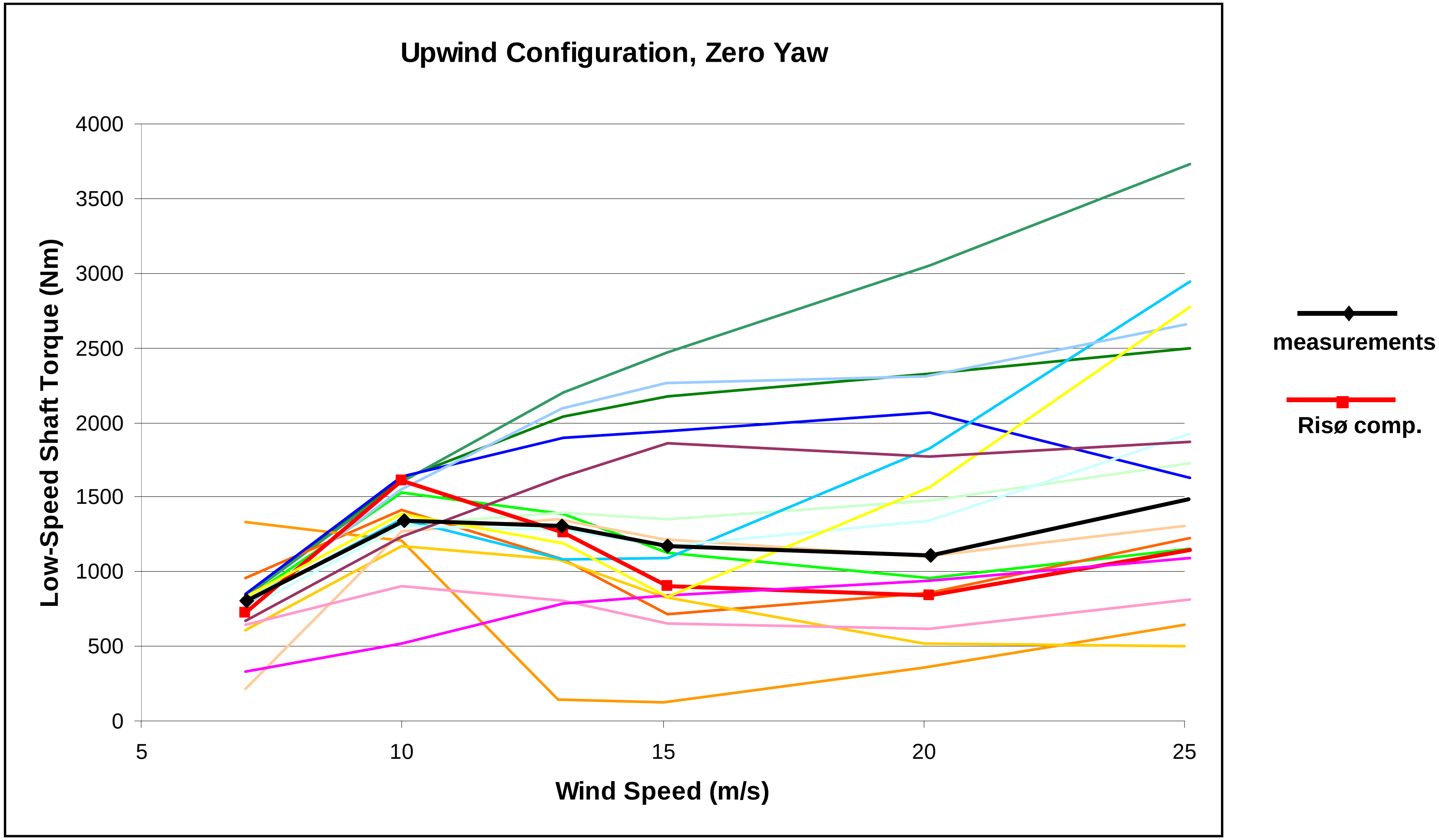
Rotor Aerodynamics
NREL / Nasa Ames test

NASA Ames Tunnel (24.4x36.6 m)

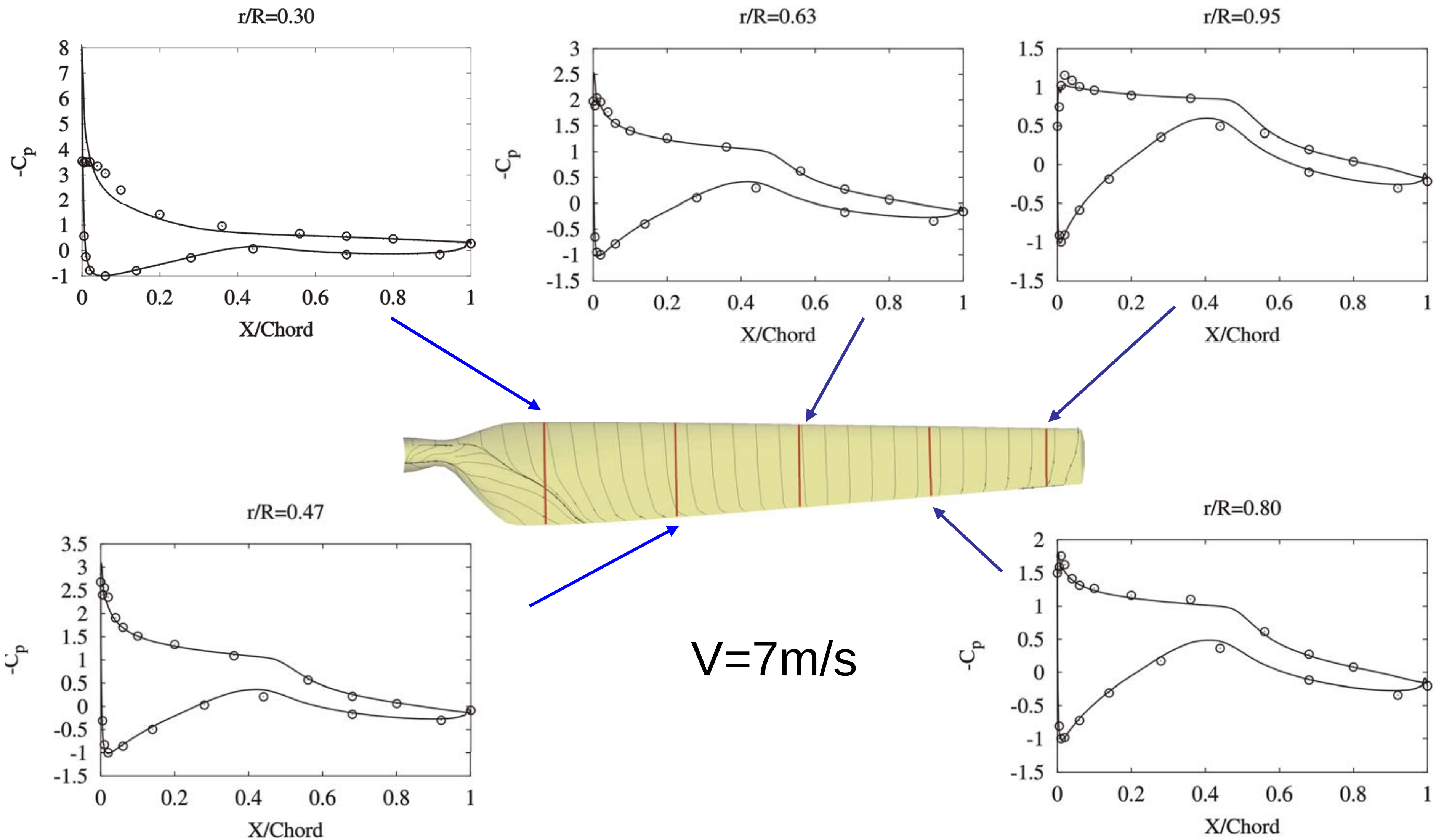


NREL Phase-VI Wind Turbine

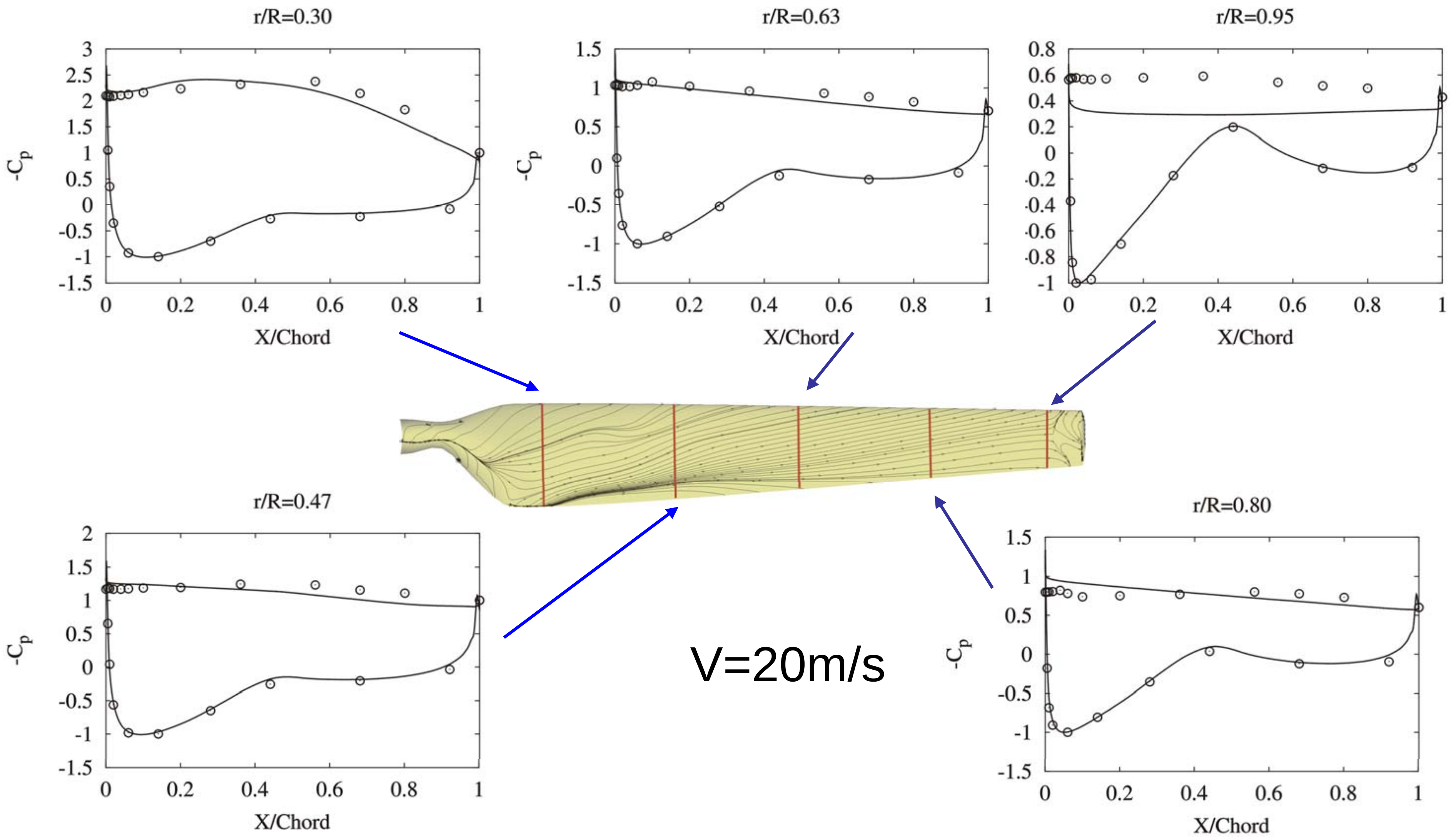
Rotor Aerodynamics
Blind Comparison



Rotor Aerodynamics
NREL Phase-VI rotor, Cp. distribution

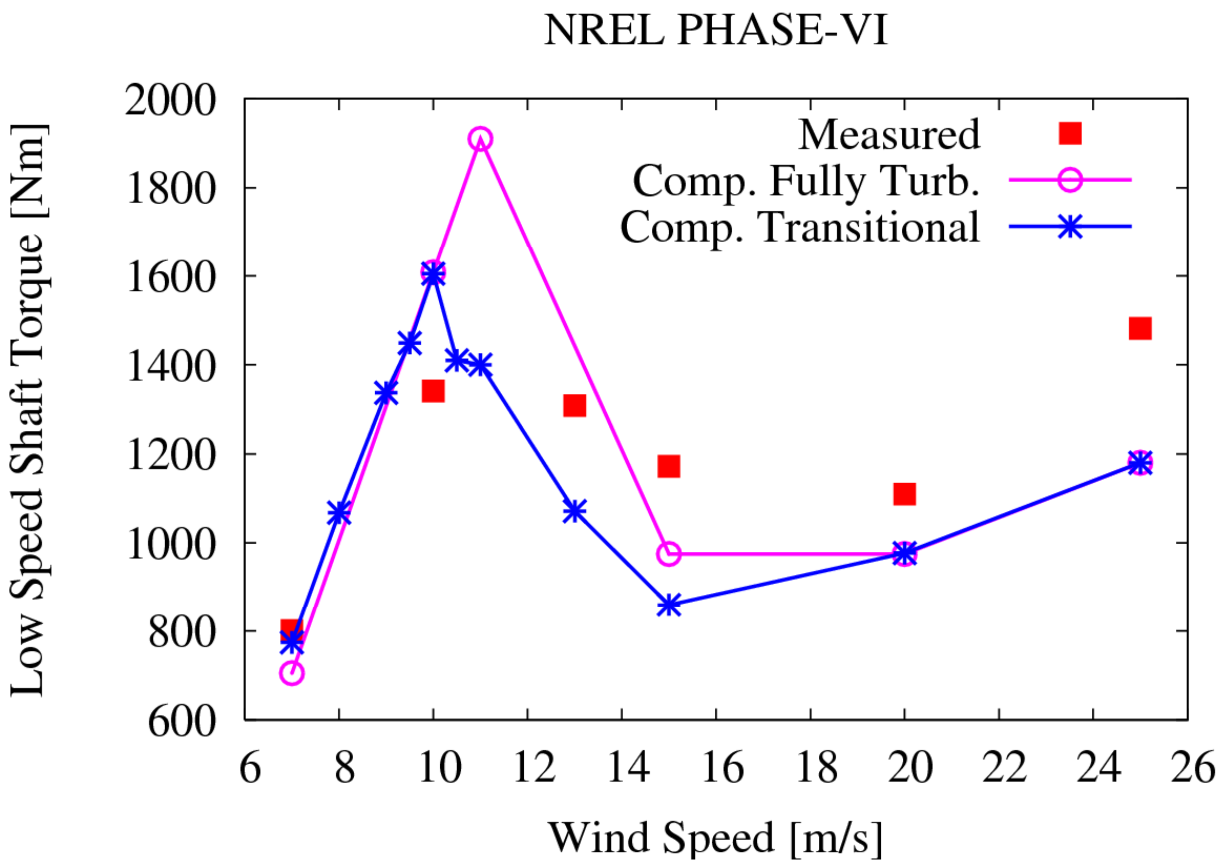


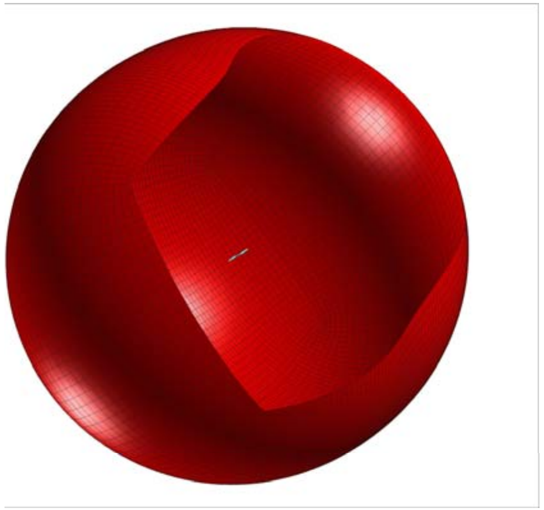
Rotor Aerodynamics
NREL Phase-VI rotor, Cp. distribution



Rotor Aerodynamics
NREL Phase-VI rotor, Laminar/turbulent transition

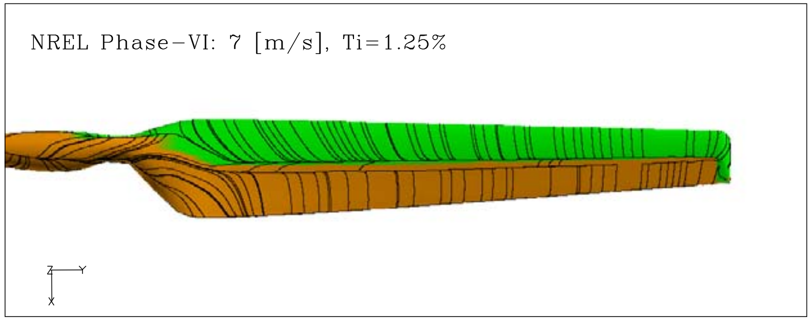
The transition model can improve the results in some cases

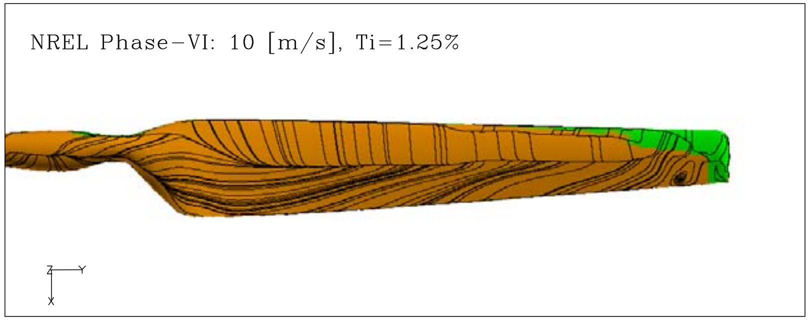


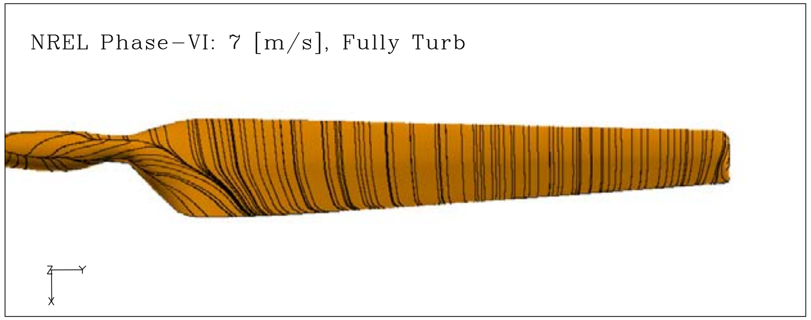


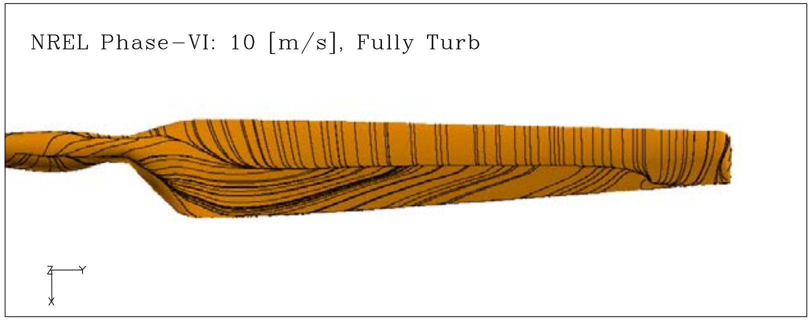
Rotor Aerodynamics
NREL Phase-VI rotor, Laminar/turbulent transition

- Limiting streamlines



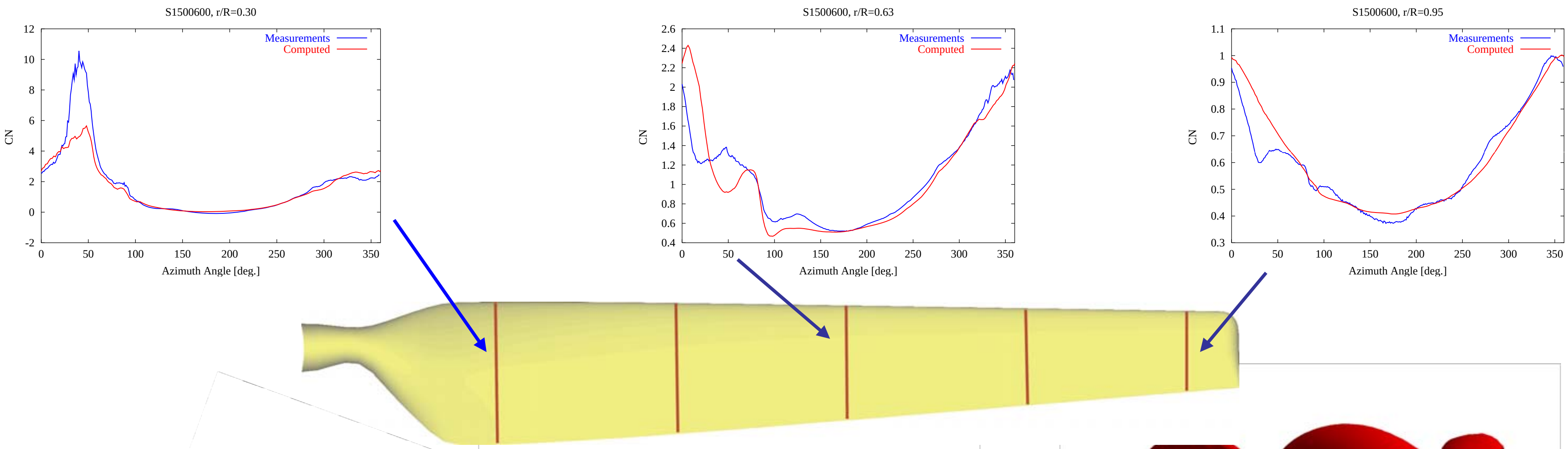


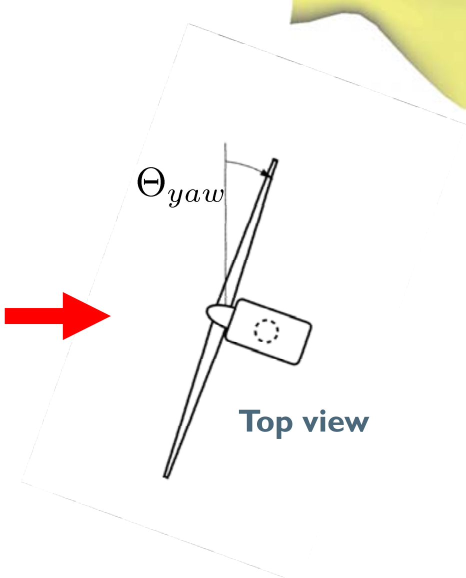


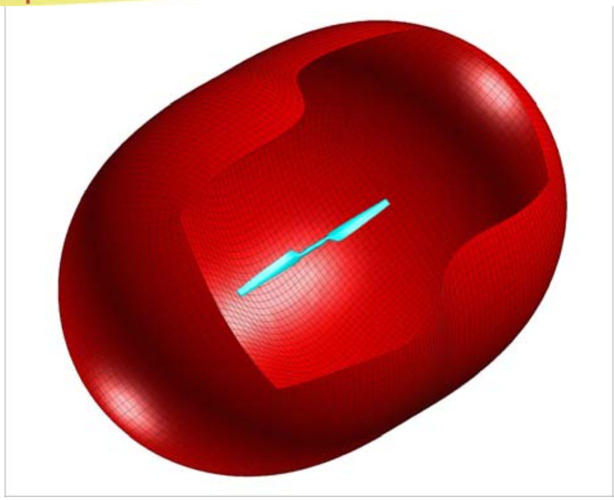


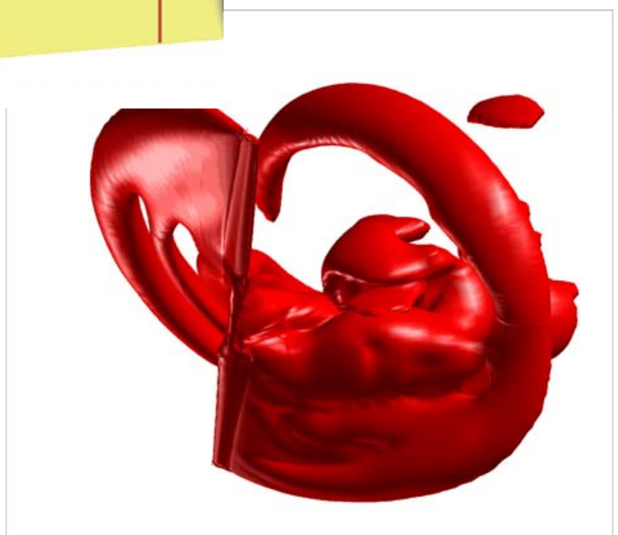
Rotor Aerodynamics
Yaw computations (60 degrees)

Azimuth variation of normal force

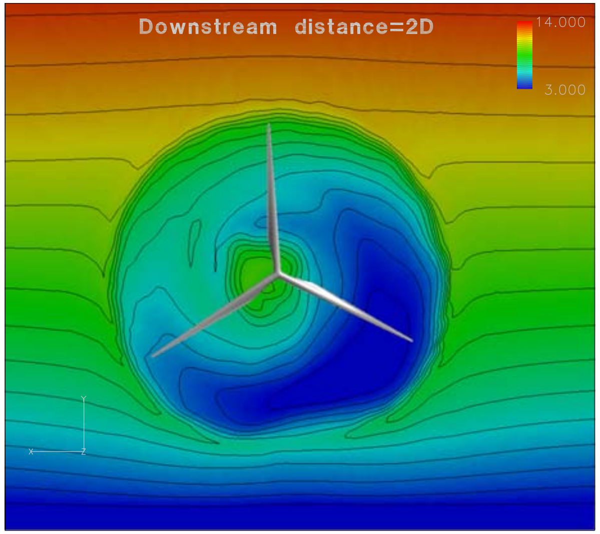




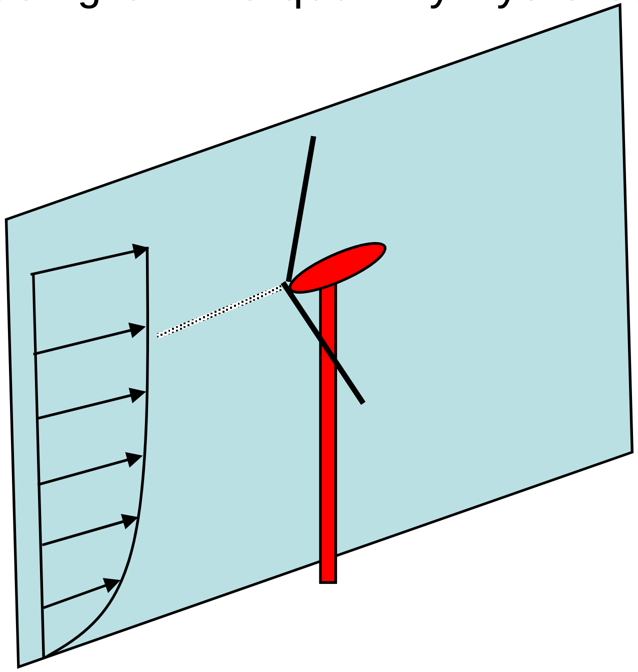




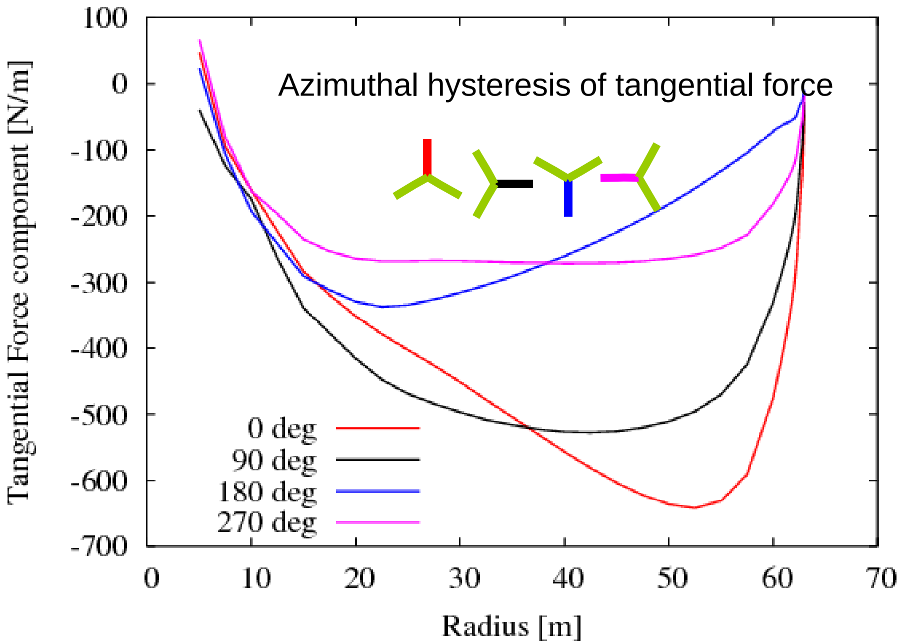
Rotor Aerodynamics
Rotors in atmospheric shear



- Rotors in shear flow has been studied using CFD to quantify hysteresis effects

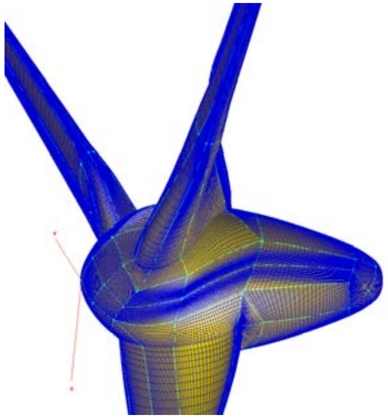


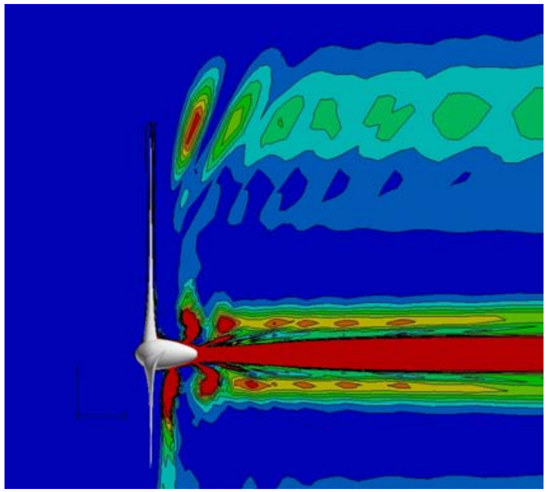
$$U(z) = 8m/s\left(\frac{z}{90m}\right)^{0.55}$$



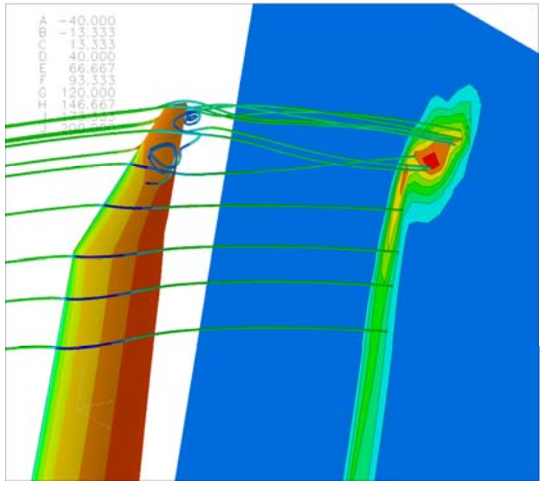
Rotor Aerodynamics
Detailled design analysis

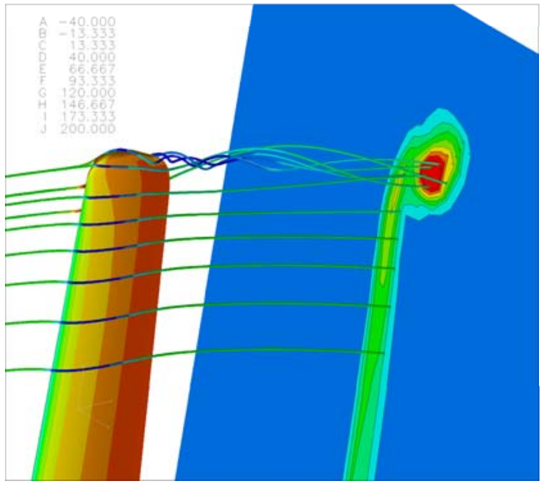
Enercon E-70 design





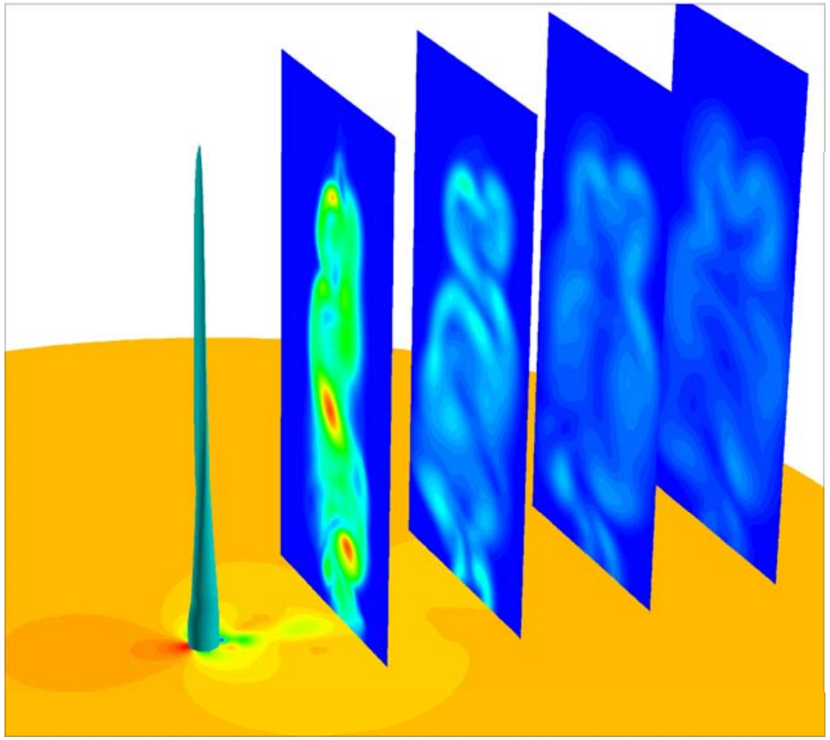
Tip-design

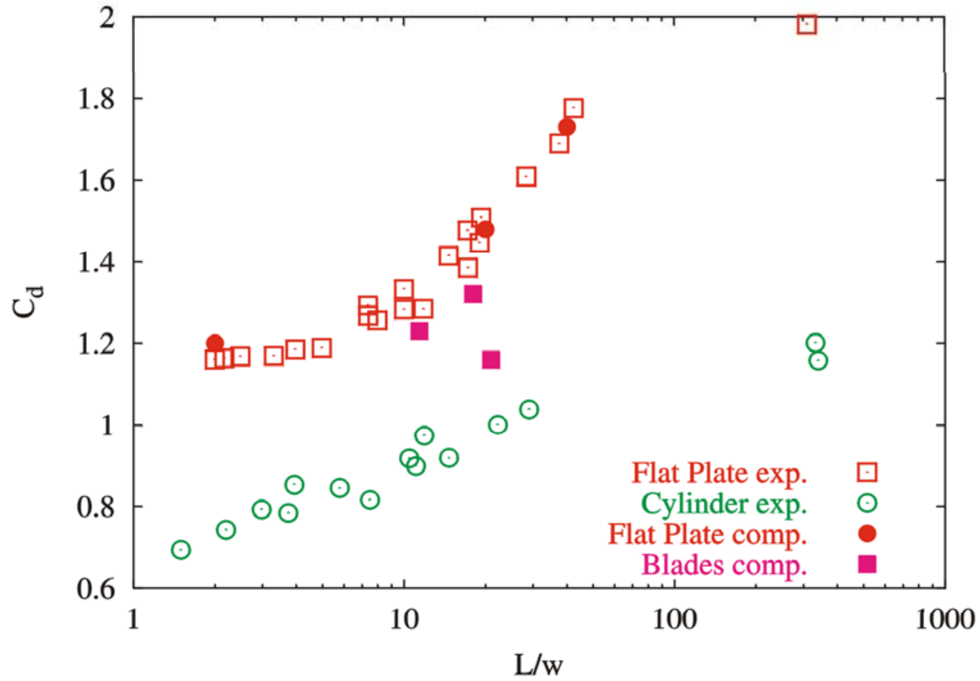




Rotor Aerodynamics
Drag values for parked wind turbine blades

Definition of aspect ratio
$L/w = L^2/\text{Area}$

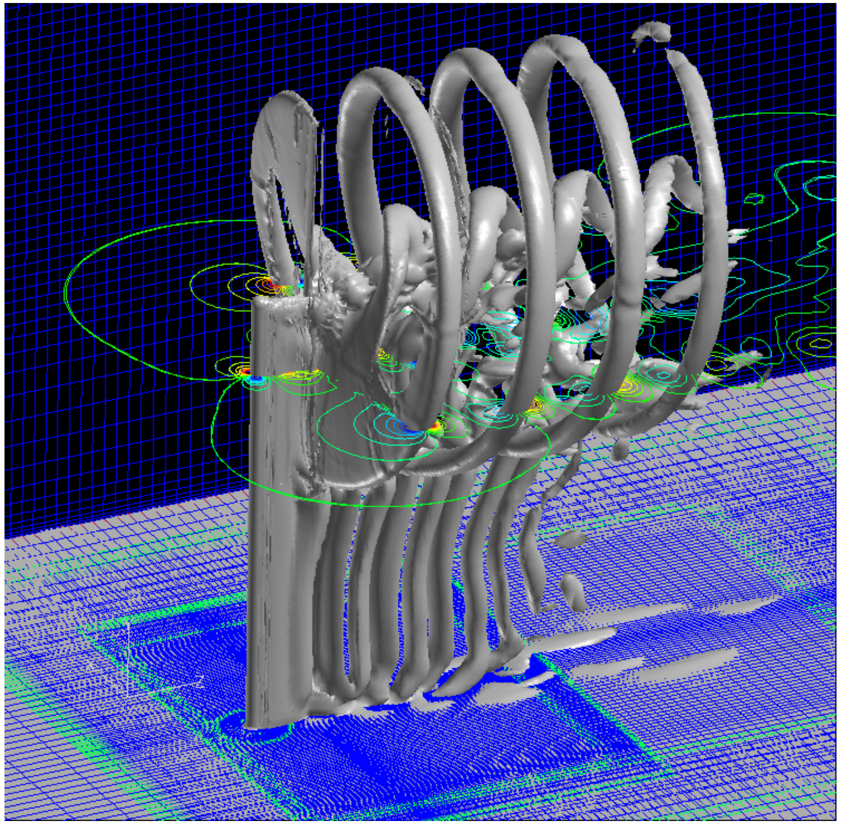


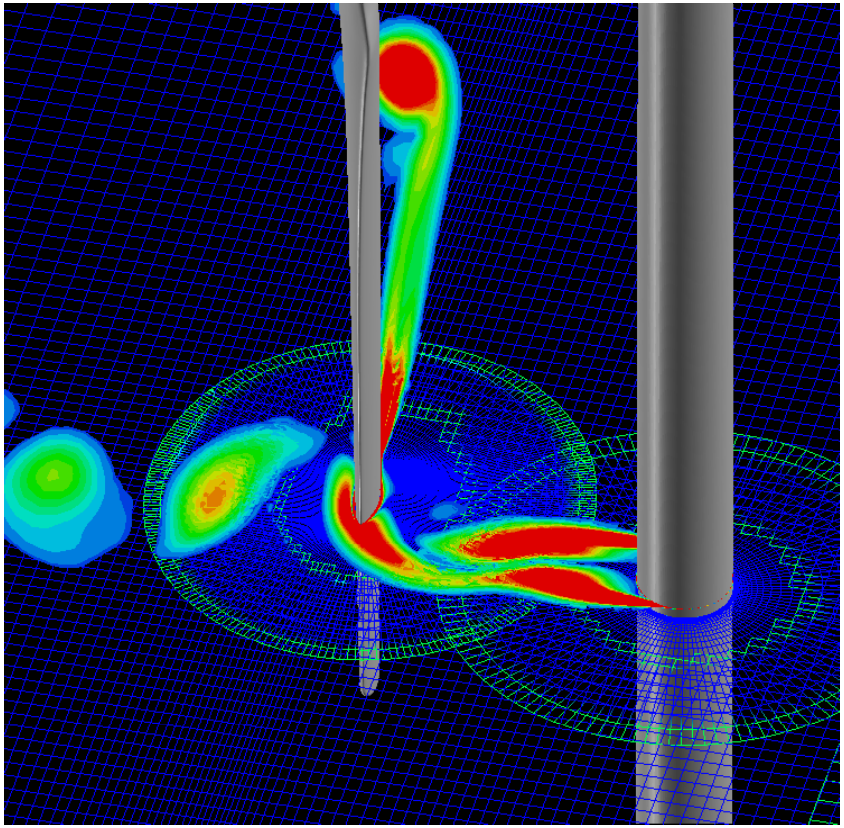


Blade	L/w	C_d comp.
LM8.2	11.4	1.23
LM19.1	18.0	1.32
Modern	21.0	1.16

Rotor Aerodynamics
Rotor tower interaction

Details of blade-tower interaction investigated in order to:
- study lock-in phenomina
- develop semi-emperical tower shadow model and noise model



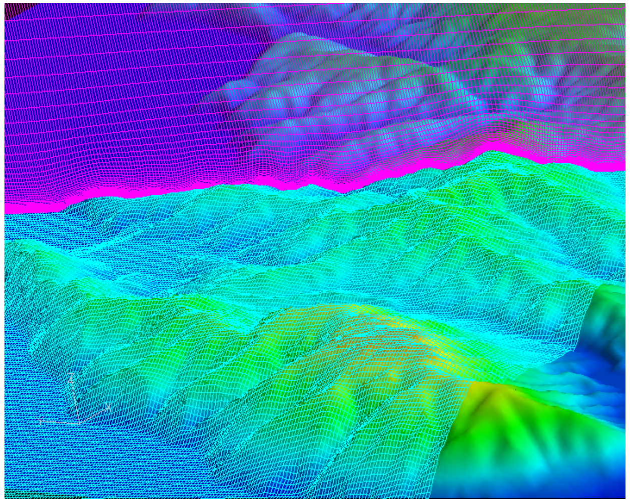


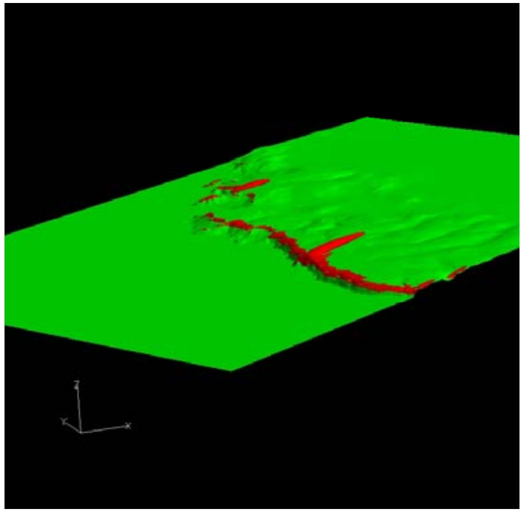
Site Analysis
Complex Terrain

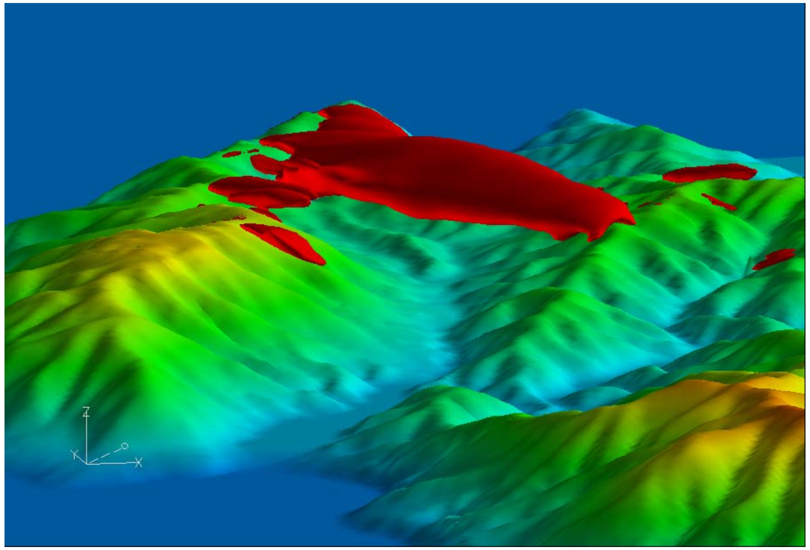
Terrains where WAsP is not suitable

Determining Speed-up, and flow inclination

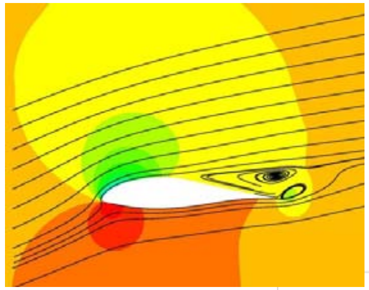
Evaluation of turbine positions, from levels of turbulent kinetic energy

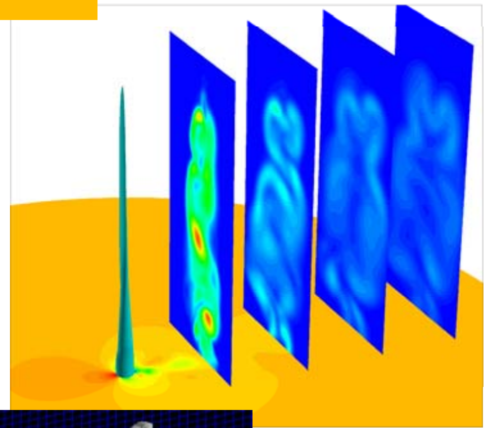






Conclusion





- A CFD methodology suited for wind energy has been introduced
- A series of applications of CFD to wind energy, including airfoil and rotor aerodynamics has been given, illustrating the possibilities.